Getting ready for the LHC: a QCD status report

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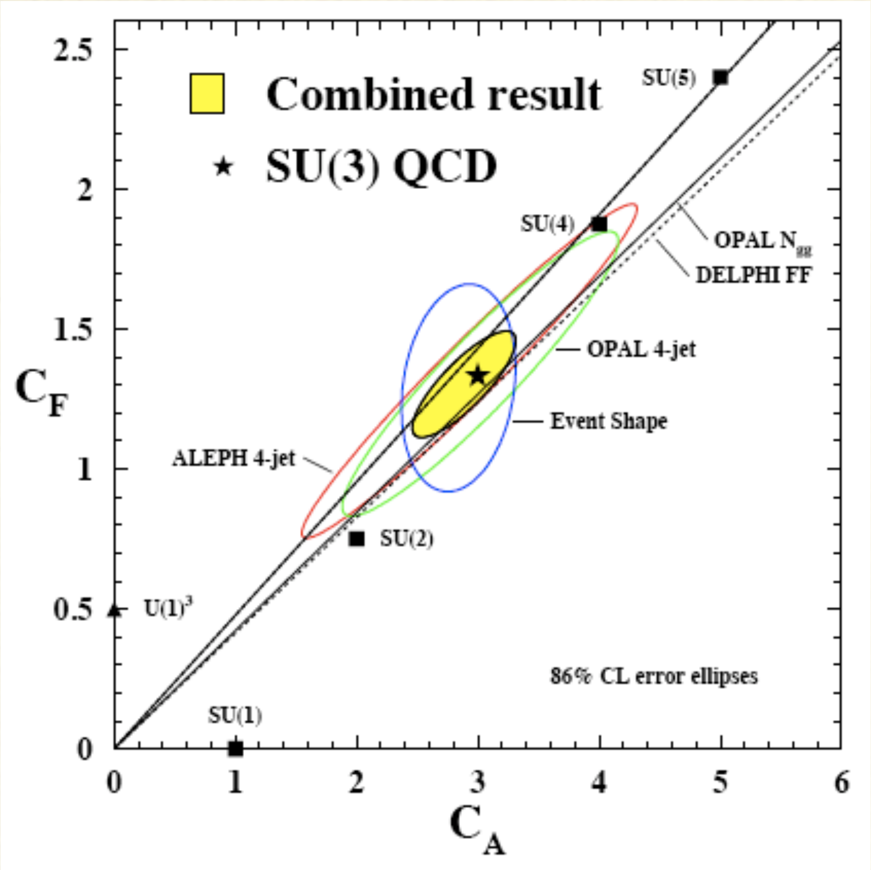
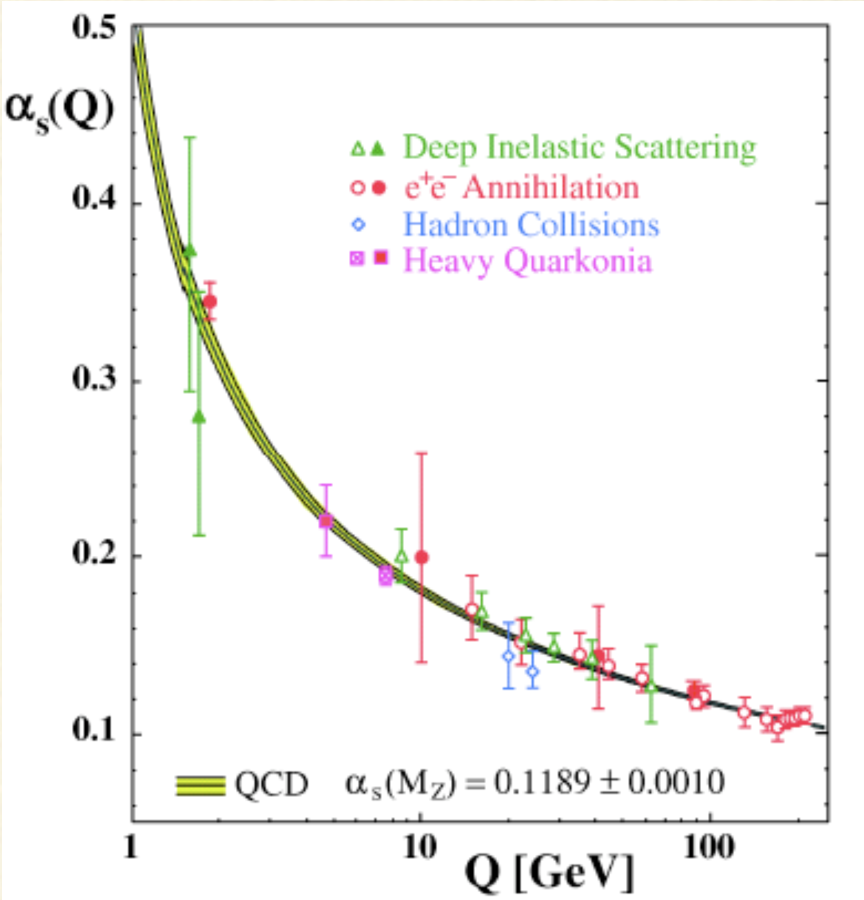
Outline

- Introduction
- Structure of QCD at the LHC
- Cross section predictions in pQCD
- Matrix elements and parton showers
- Parton distribution functions
- Conclusions

Status of pQCD

S. Bethke '06



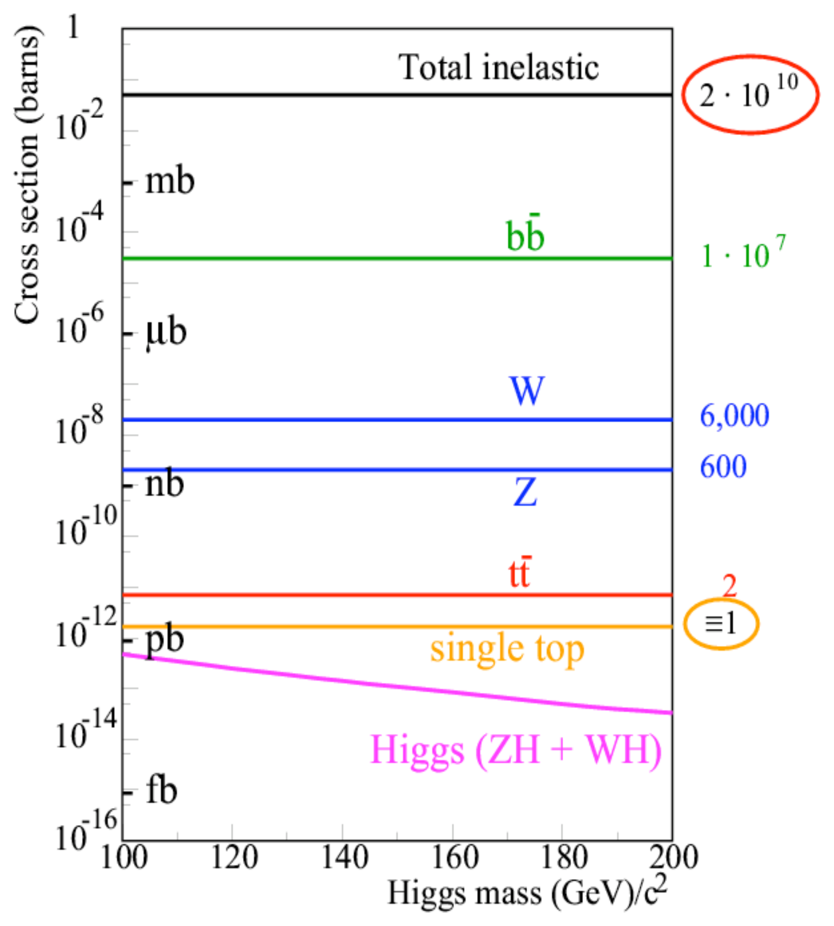


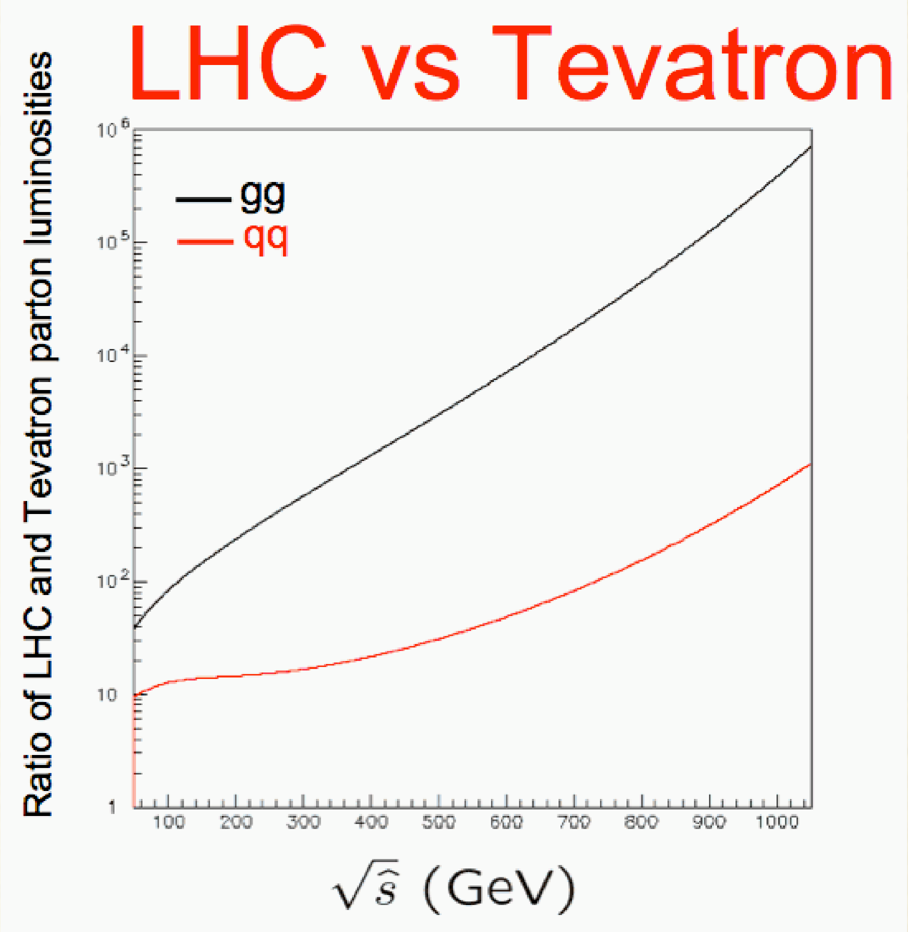
Perturbative QCD established as correct theory

LHC focus on QCD as background to new high pT physics

Rates at the LHC

T. LeCompte, '07 CTEQ summer school

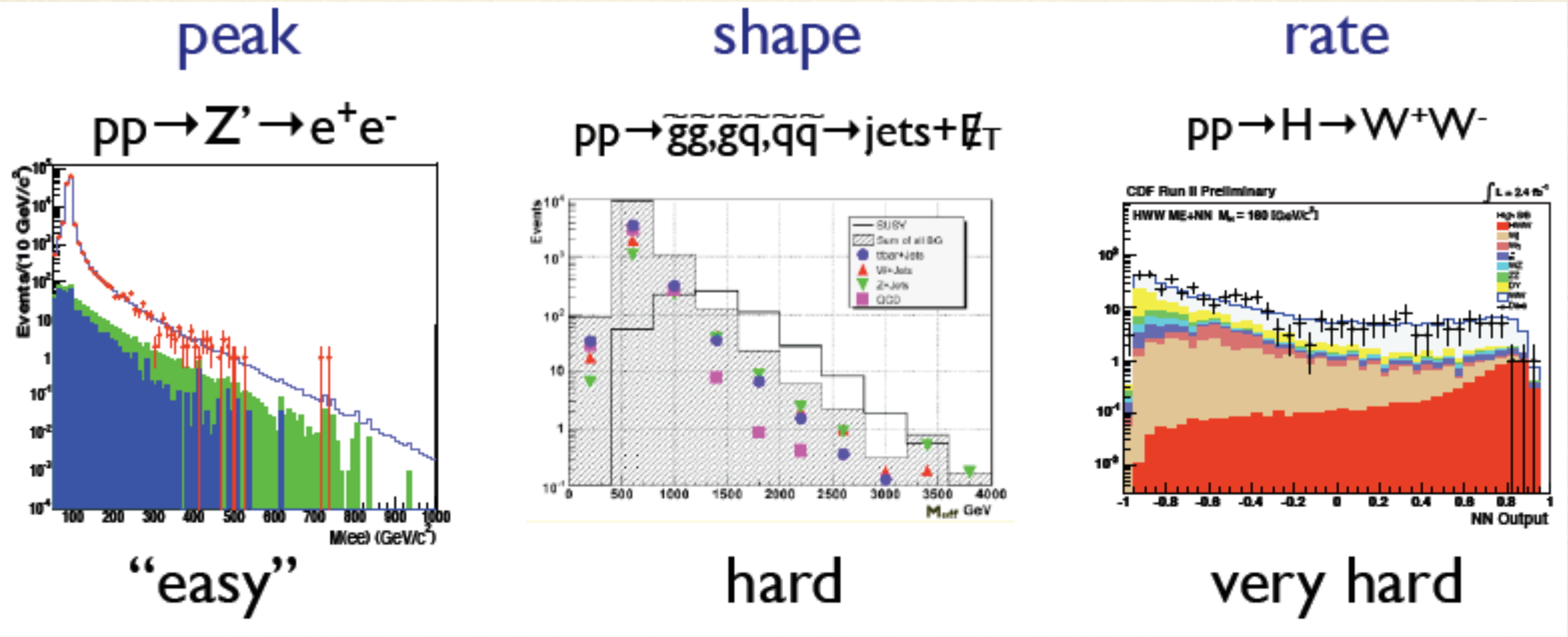




Enormous challenge to understand as required!
Gluon density? Understand signal, background well enough for orders of magnitude background reduction? To measure new physics parameters?

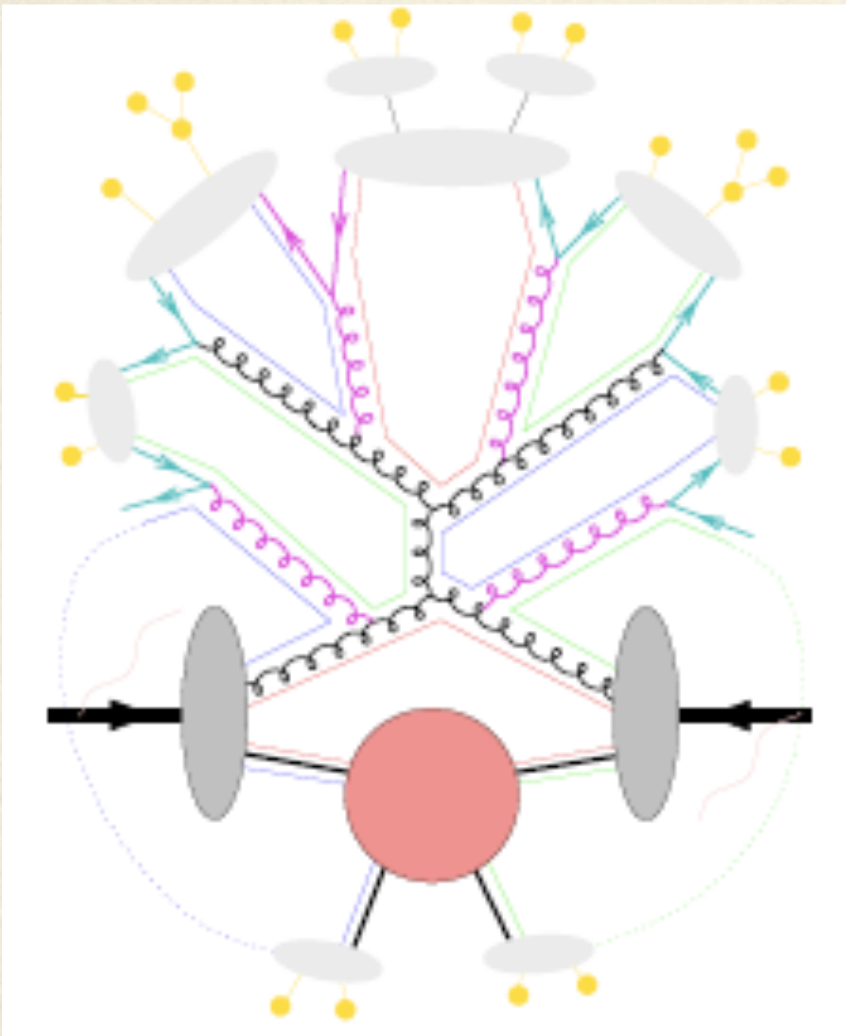
“Easy” and “Hard” discoveries

F.Maltoni ‘08



Not all signals contain clear peak over background;
this is when theory is needed

Collisions at the LHC



A lot going on...

- New Physics at hard scale; M_H , for example
- Parton shower evolution from M_H to Λ_{QCD}
- Final-state hadronization at Λ_{QCD}
- Parton distributions at Λ_{QCD}
- Multiple parton interactions, hadron decays, ...

Factorization

Make sense of this with *factorization:* separate hard and soft scales (divide and conquer)

$$N_{events} = L \int dx_1 dx_2\, f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2) \sigma_{ij}(x_1, x_2, \mu_F^2) + O\left(\left[\frac{\Lambda_{QCD}}{Q}\right]\right)$$

Luminosity   Parton momentum fractions   PDFs   Hard cross section   Power corrections

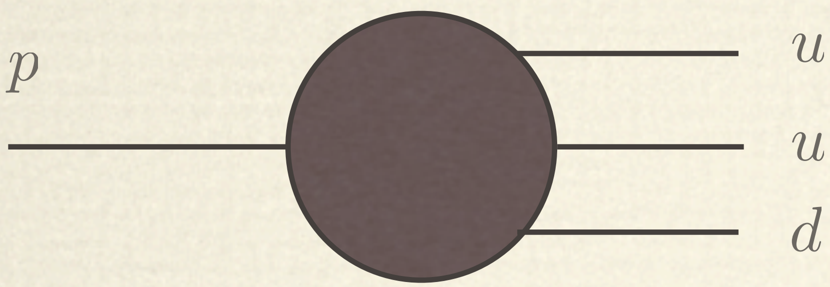
Cross sections: pQCD, can calculate

PDFs: non-perturbative, must measure

For sufficiently inclusive observables, power corrections small

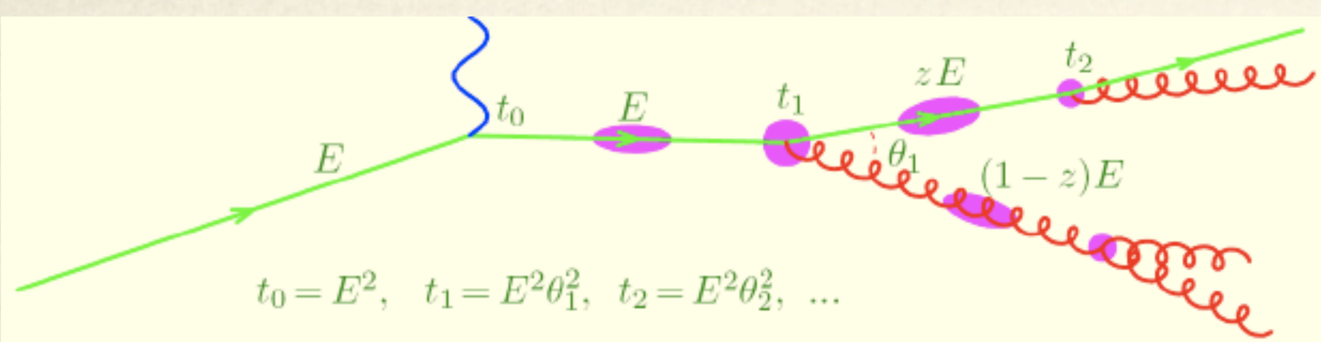
Warning! Not proved for all processes Collins, Qiu '07

Universality



Factorization separates f_i from hard process; f_i are *universal*

Measure in DIS, fixed target, use at LHC



Parton shower emission of radiation controlled roughly by

Large logs: LHC very "jetty" $\quad \ln^2\left(\frac{\hat{s}}{\Lambda_{QCD}^2}\right) \sim \ln^2\left(\frac{1\ \mathrm{TeV}^2}{1\ \mathrm{GeV}^2}\right)$

With "leading log" approximation, emission is *universal*

QCD predictions at LHC

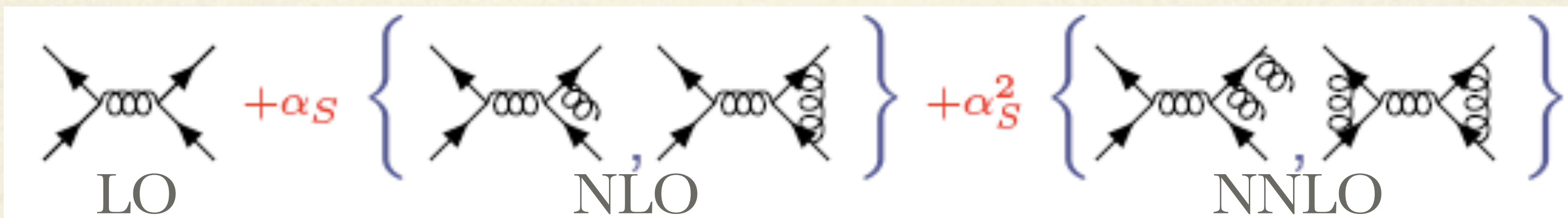
- Calculate σ_{ij} at high scale
- Evolve initial, final states to Λ_{QCD} using parton shower
- Connect initial state to f_i , final state to hadronization model

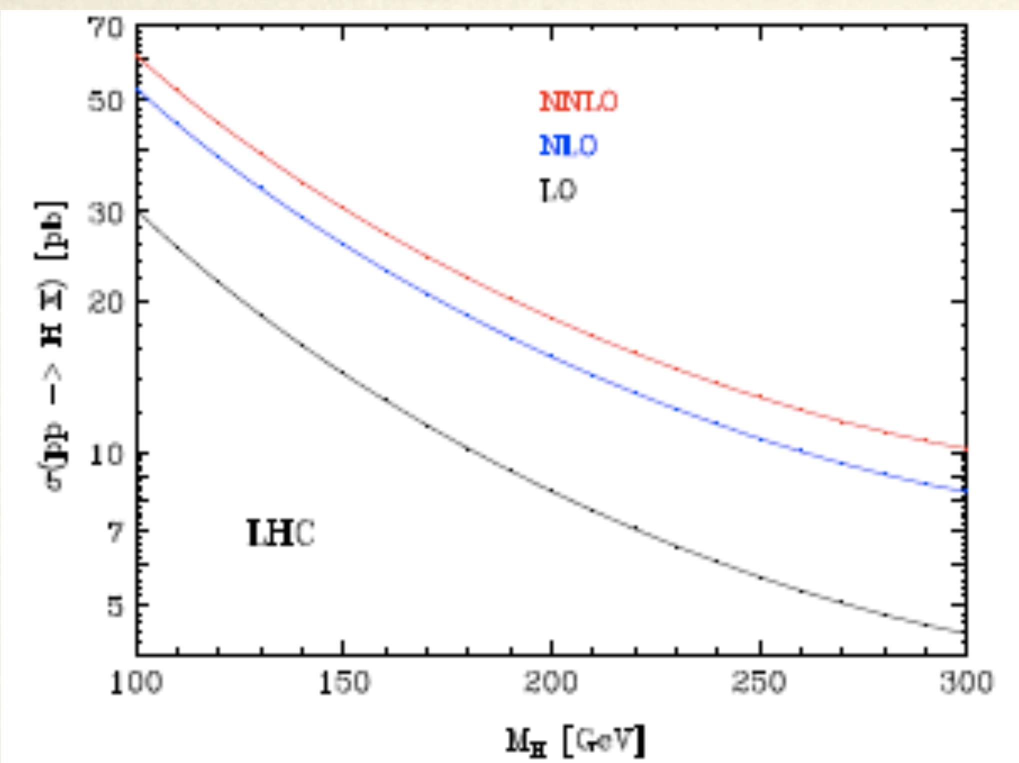
Will proceed from $\sigma_{ij} \to \mathrm{PS} \to f_i$

Emphasize important points, new results

pQCD cross sections

$$\sigma = \sigma_0 \left\{ 1 + \alpha_S \sigma_1 + \alpha_S^2 \sigma_2 + \mathcal{O}(\alpha_S^3) \right\}$$





Corrections larger than $\alpha_S \sim 0.1$ estimate!

Typically 30-100%

- New partonic channels beyond LO
- Additional kinematic regions from recoil
- Large coefficients (π^2 from analytic cont.)

Need at least NLO at LHC!

Status of NLO cross sections

C. Oleari

Process ($V \in \{Z, W, \gamma\}$)	background to/ relevant for	status
$pp \to V\,V\,V$	SUSY tri-lepton	ZZZ: Lazopoulos, Melnikov, Petriello (07)
		Binoth, Ossola, Papadopoulos, Pittau (08)
$pp \to V\,V\,V \to$ 6 leptons (full spin corr.)		WWZ: Hankele, Zeppenfeld (07)
		ZZW and WWW to appear soon
$pp \to VV + 1$ jet	$t\bar{t}H$, new physics	$WW + 1$ jet: Dittmaier, Kallweit, Uwer (07)
		$WW + 1$ jet + decay: Campbell, Ellis, Zanderighi (07)
		Binoth, Karg, Kauer, Sanguinetti (in progress) $\Rightarrow'$ 08
$pp \to VV + 2$ jets $\to$ 4 lept. + 2 jets via VBF	VBF $H \to VV$ & VV coupl.	(Bozzi), Jäger, Oleari, Zeppenfeld (07)
$pp \to V + 2$ jets (b)		Campbell, Ellis, Maltoni, Willenbrock (06)
$pp \to V b\bar{b}$		Febres-Cordero, Reina, Wackeroth (07)
$pp \to H + 2$ jets via VBF	VVH couplings	QCD + EW: Ciccolini, Denner, Dittmaier (07)
$pp \to H + 2$ jets via gluon fusion	H via VBF	QCD: Campbell, Ellis, Zanderighi (06)
$pp \to H + 3$ jets via VBF (large N_c)		Figy, Hankele, Zeppenfeld (07)
$pp \to t\bar{t} + 1$ jet		Dittmaier, Uwer, Weinzierl (07)
		Ellis, Giele, Kunszt (in progress) $\Rightarrow'$ 08 with Melnikov
$pp \to t\bar{t}Z$	SUSY tri-lepton	Lazopoulos, McElmurry, Melnikov, Petriello (08)
$gg \to WW$		Binoth, Ciccolini, Kauer, Kramer (06)
$gg \to HH(H)$		Binoth, Karg, Kauer, Rückl (06)
$gg \to gggg$ (amplitude only)		$\ldots$, Xiao, Yang, Zhu (06)
$\gamma\gamma \to \gamma\gamma\gamma\gamma$ (amplitude only)		Nagy, Soper (06); Binoth, Heinrich, Gehrmann, Mastrolia (07)
		Ossola, Papadopoulos, Pittau (07); Forde (07)

$+pp \to t\bar{t}b\bar{b}$ 

Bredenstein, Denner, Dittmaier, Pozzorini '08

$Wjjj$ amps Ellis, Giele, Kunszt, Melnikov, Zanderighi '08

Very active: Anastasiou, Anderson, Badger, Bena, Berger, Bern, Bernicot, Bidder, Binoth, Brandhuber, Britto, Buchinder, Cachazo, Ciccolini, Del Duca, Denner, Dixon, Dunbar, Ellis, Feng, Febres Cordero, Forde, Giele, Glover, Guffanti, Guillet, Heinrich, Ita, Karg, Kauer, Kilgore, Kosower, Kunzst, Mastrolia, Maitre, Melnikov, Nagy, Ossola, Papadopoulos, Passarino, Perkins, FP, Pilon, Pittau, Reiter, Risager, Roiban, Roth, Sanguinetti, Schubert, Schwinn, Smillie, Soper, Spence, Travaglini, UWer, Weinzierl, Weiders, Yang, Zanderighi, ...

Many new results!

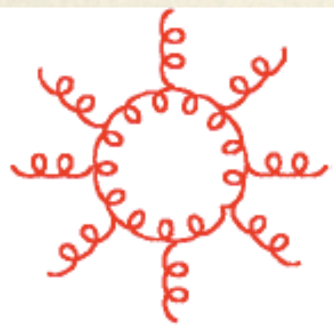
By multiplicity:

- $2 \to 2$: easy
- $2 \to 3$: difficult (algebraic complexity, spurious singularities) but understood in past few years
- $2 \to 4$: new frontier, only $t\bar{t}b\bar{b}$ $Wjjj$ amps

Multi-leg problems

Avoid traditional computation of loop diagrams with Feynman rules

Z. Bern



+ 3,017,489 other diagrams

8-gluon amplitude

#gluons	Diagrams
4	4
5	25
6	220
7	2, 485
8	34, 300
9	559, 405
10	10, 525, 900

at tree level

(miracle #4)

$$A(p_1^-,p_2^+,p_3^-,p_4^+,\dots,p_n^+) = \frac{\langle 1\,3\rangle^4}{\langle 1\,2\rangle\langle 2\,3\rangle\dots\langle n-1\,n\rangle\langle n\,1\rangle}$$

(Parke, Taylor 1986; Berends, Giele 1989)

$$A(1^-,2^-,3^-,4^+,\dots,n^+)$$

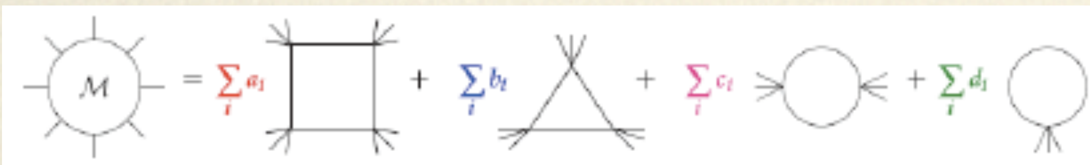
(RB, Feng, Roiban, Spradlin, Volovich 2005)

$$\frac{1}{\prod_{k=3}^{n}\langle k\,k+1\rangle}\sum_{i=4}^{n-1}\frac{\langle 1|P_{2,i}P_{i+1,2}|3\rangle^3}{P_{2,i}^2\,P_{i+1,2}^2}\frac{\langle i+1\,i\rangle}{[2|P_{2,i}|i+1\rangle\langle i|P_{i+1,2}|2]}$$

Factorial growth of diagrams, final results simpler than intermediate steps; better organizing principle?

New approaches

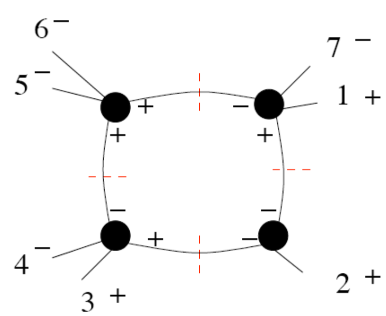
Use *unitarity* to get loops from trees



$$\frac{1}{2}\sum_{\mathcal{S}} A_1^{\rm tree} A_2^{\rm tree} A_3^{\rm tree} A_4^{\rm tree}$$

$\mathcal{S}$ is the set of all solutions of the on-shell conditions for the internal lines.

$$\mathcal{S} = \{\, \ell \mid \ell^2 = 0, \quad (\ell - K_1)^2 = 0, \quad (\ell - K_1 - K_2)^2 = 0, \quad (\ell + K_4)^2 = 0 \}$$

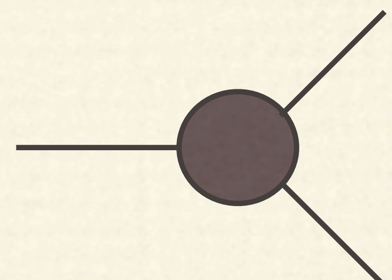


$$\text{coeff} = \frac{1}{2}\frac{[\ell_1\,\ell_4]^3}{[\ell_1\,2][2\,\ell_4]}\frac{[4\,\ell_2]^3}{[\ell_2\,\ell_1][\ell_1\,3][3\,4]}\frac{[5\,6]^3}{[6\,\ell_3][\ell_3\,\ell_2][\ell_2\,5]}\frac{[\ell_3\,7]^3}{[7\,1][1\,\ell_4][\ell_4\,\ell_3]}$$

$$= -\frac{\langle 1\,2\rangle^3\langle 2\,3\rangle^3[5\,6]^3}{\langle 7\,1\rangle\langle 3\,4\rangle\langle 2|P_{3,4}|5]\langle 2|P_{7,1}|6]\langle 2|P_{3,4}P_{5,6}|7\rangle\langle 2|P_{7,1}P_{5,6}|4\rangle}$$

(example from R. Britto)

<u>Key observation</u>: use complex external momenta



for massless, on-shell states doesn't vanish

Britto, Cachazo, Feng '04

- Cut all propagators of multi-loop amplitudes

  (Buchbinder, Cachazo; Bern, Carrasco, Johansson, Kosower)

- Leading singularity construction for multi-loop integrals without triangle components

  (Cachazo)

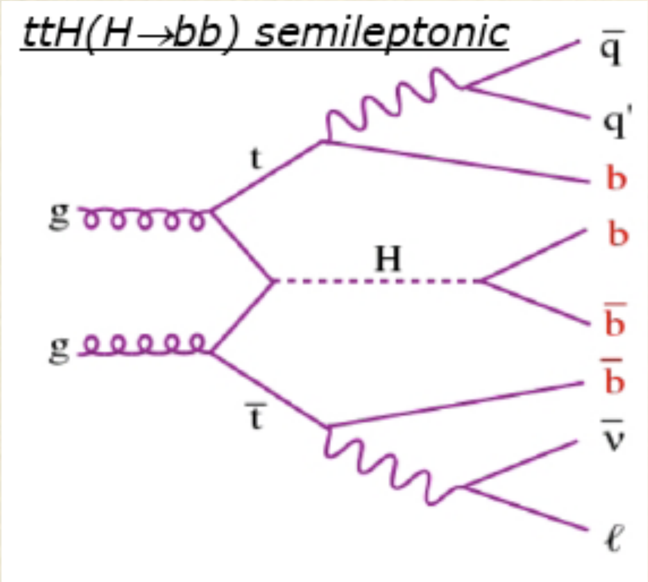
- Sequential approach to box, triangle, bubble, tadpole coefficients by quadruple, triple, double single cuts

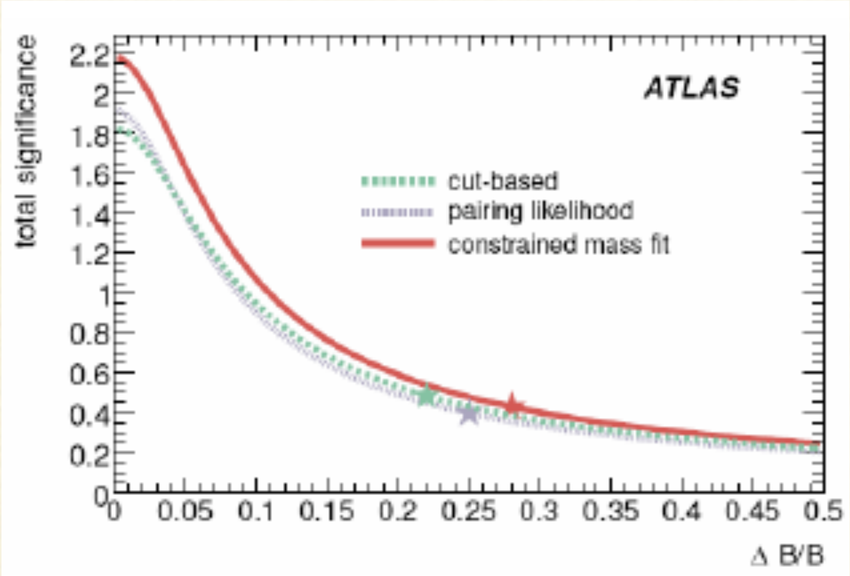
  (Ossola, Papadopoulos, Pittau; Mastrolia; Forde; Kilgore; Ellis, Giele, Kunszt; Giele, Kunszt, Melnikov)

Other new analytic, numerical approaches

ttbb at the LHC

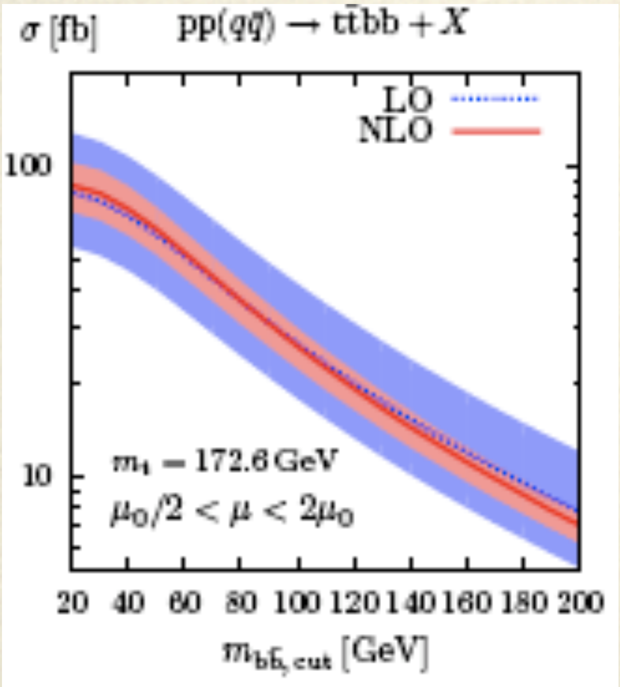
A. Nisati





Required for measurement of Higgs couplings to bottom, top quarks

→ Understanding of $t\bar{t}b\bar{b}$ background critical



New NLO result with reduced theory error; new hope of using this channel Bredenstein, Denner, Dittmaier, Pozzorini ’08

NEW

First $2 \longrightarrow 4$ LHC NLO calculation

Status of NNLO cross sections

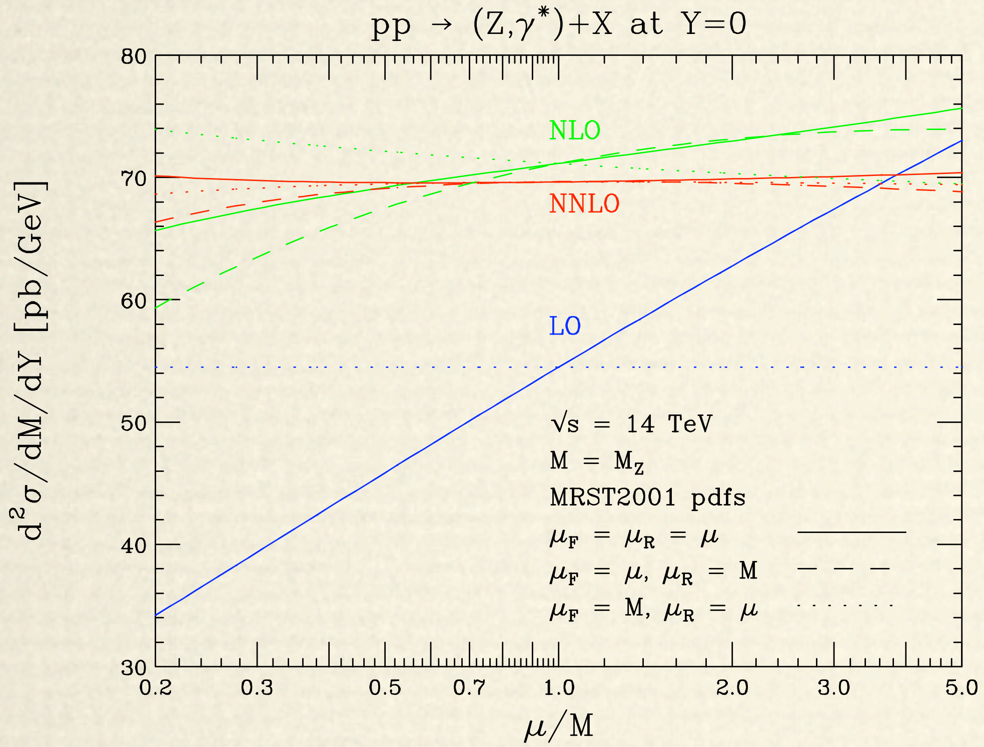
When is NNLO necessary?

- When corrections are large at NLO, and NNLO is needed for accurate rate predictions $(gg \to H)$
- For benchmark precision where high precision is required (Drell-Yan, $e^+e^- \to 3$ jets)

How to arrange cancellation of infrared divergences for differential calculations?

- Automated, numerical via sector decomposition (Anastasiou, Melnikov, FP)
- Analytic subtraction schemes (Gehrmann-De Ridder, Gehrmann, Glover, Heinrich; Catani, Grazzini; Weinzierl)

Drell-Yan



Anastasiou, Dixon, Melnikov, FP ’03; Melnikov, FP ‘06

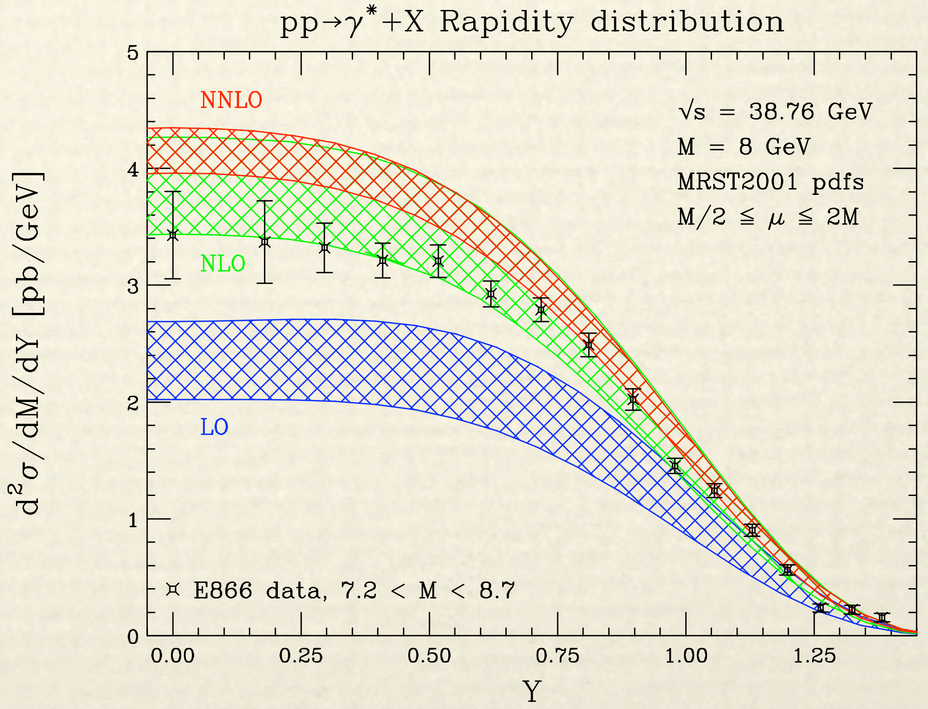
Most precisely known LHC cross section

Theory uncertainty: 1% at NNLO

Use to normalize LHC luminosity:

$$N_X = \left(\frac{\sigma_X}{\sigma_Z}\right)_{th} N_Z$$

Important effect on PDFs



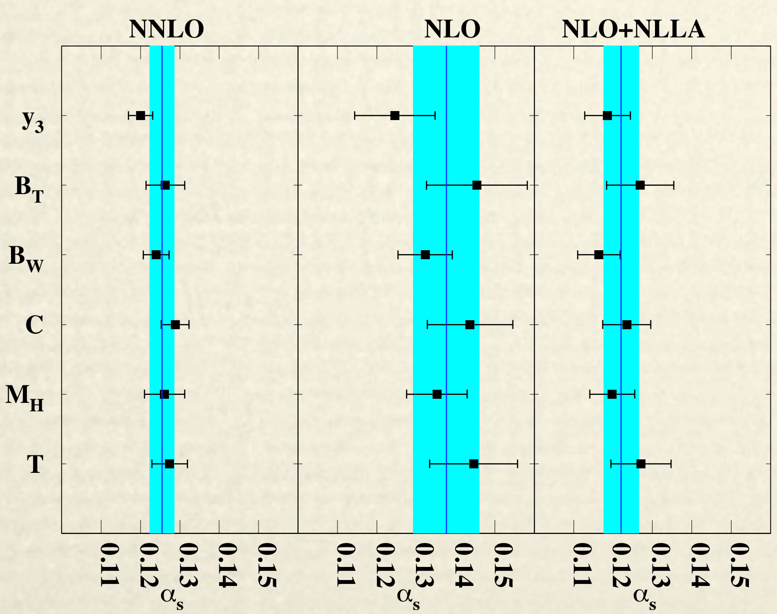
e+e- to 3 jets

Limiting factor in α_S extraction was theory:

$$\alpha_S(M_Z) = 0.1202 \pm 0.0003\,(\mathrm{stat}) \pm 0.005\,(\mathrm{th.})$$ LEP QCD WG

Recent NNLO calculation of 3 jet event shapes Gehrmann-De Ridder, Gehrmann, Glover, Heinrich; Weinzierl '07,'08

Use SCET to resum thrust distribution Becher, Schwartz '08



$$\alpha_S(M_Z) = 0.1172 \pm 0.0022$$

from Becher, Schwartz

ME vs. PS

If we integrate over final-state radiation, can use low-multiplicity fixed-order results

Otherwise, need other approaches

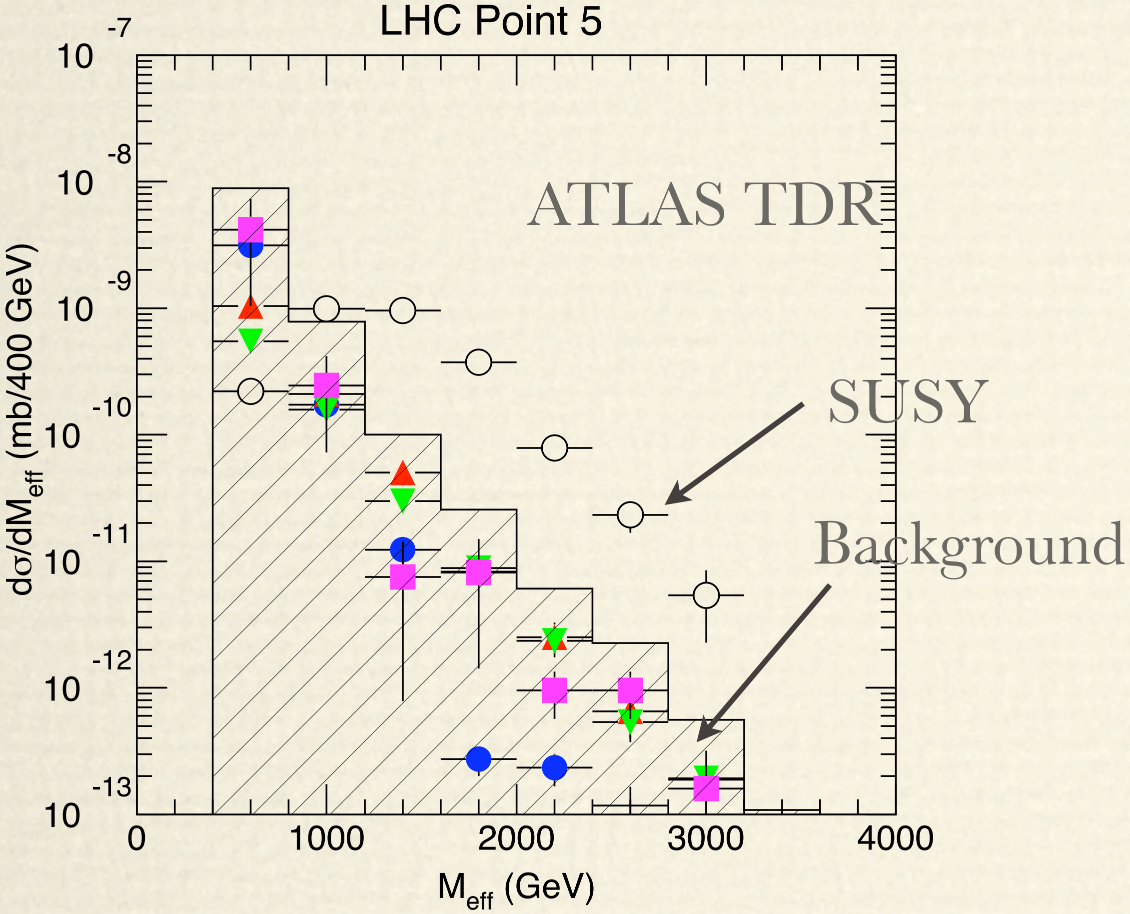
- Matrix elements: W+n jets, etc. Valid for hard, separated partons. Only LO for n>2.
- For soft/collinear partons, MEs have $\ln\left(\frac{M^2}{p_T^2}\right), \ln\left(\Delta\phi^2\right)$

Parton showers resum these at leading log (universal)

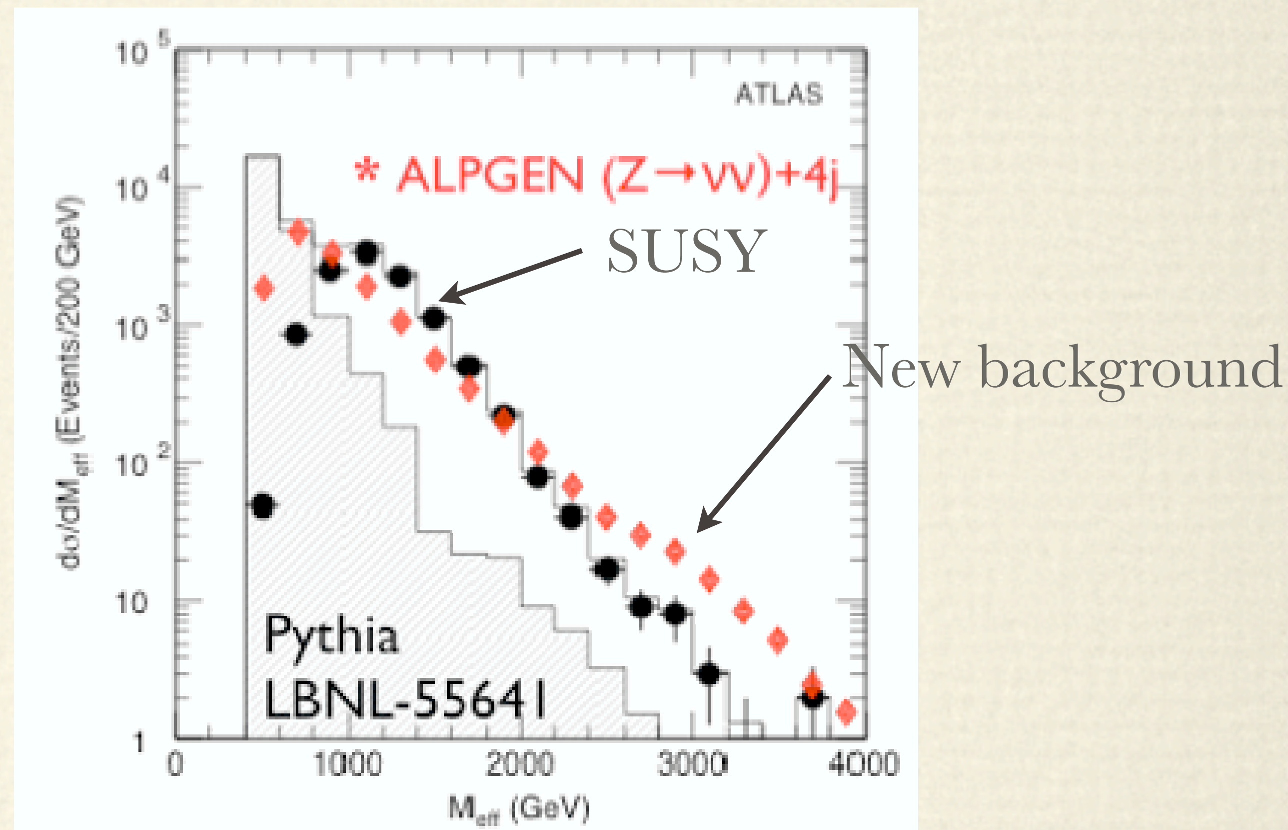
Many processes, high-multiplicity for connection to hadronization

HERWIG, PYTHIA, SHERPA, ...

The wrong tool...



Gianotti, Mangano '05



Parton showers can badly underestimate hard emissions; MEs can get low pT regions drastically wrong

ME+PS

Want to describe all regions of phase space

➡ need to merge multi-parton ME and PS

CKKW (Catani, Krauss, Kuhn, Webber); MLM (Mangano)

Can only get normalization from higher-order pQCD

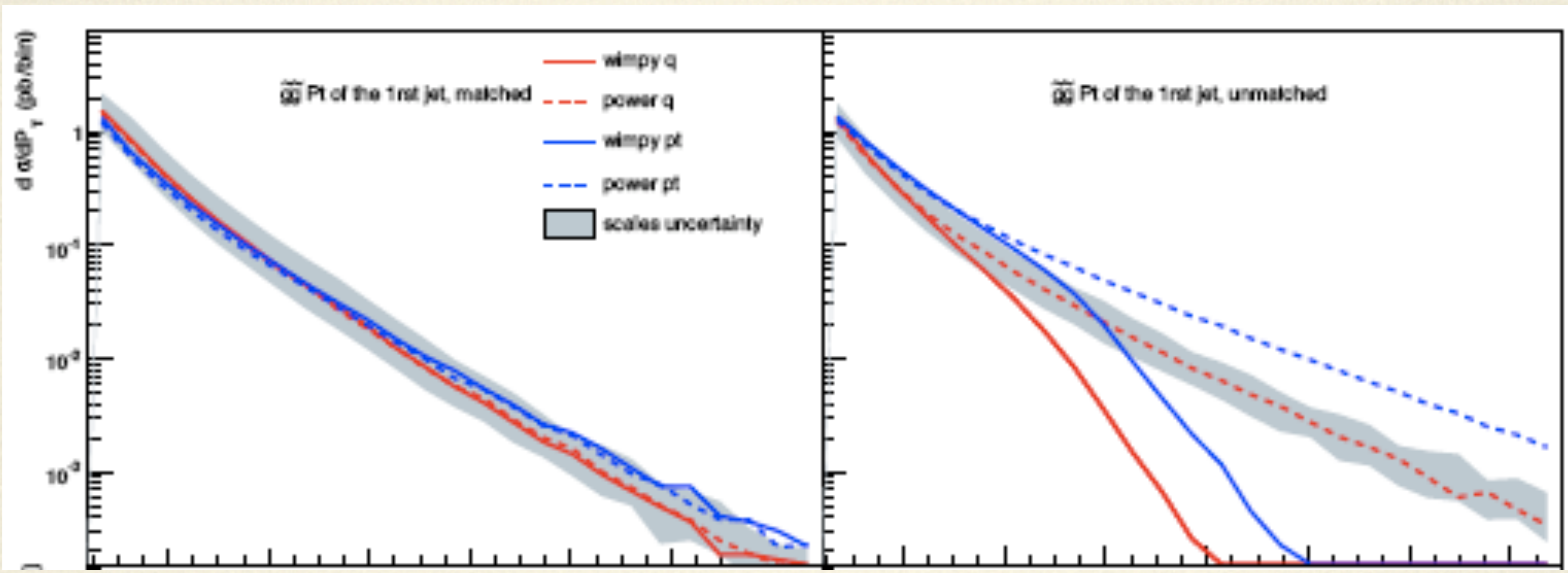
➡ need to merge NLO and PS

MC@NLO (Frixione, Webber); POWHEG (Nason, Oleari)

Very active area! Bauer, Tackmann, Thaler; Frixone, Nason, Oleari; Catani, Krauss, Kuhn, Webber; Mangano; Alwall, Demin, de Visscher, Frederix, Herquet, Maltoni, Plehn, Rainwater, Stelzer; Gleisberg, Hoche, Schalicke, Schumann, Winter; Kilian, Ohl, Reuter; ...

Tune sensitivity

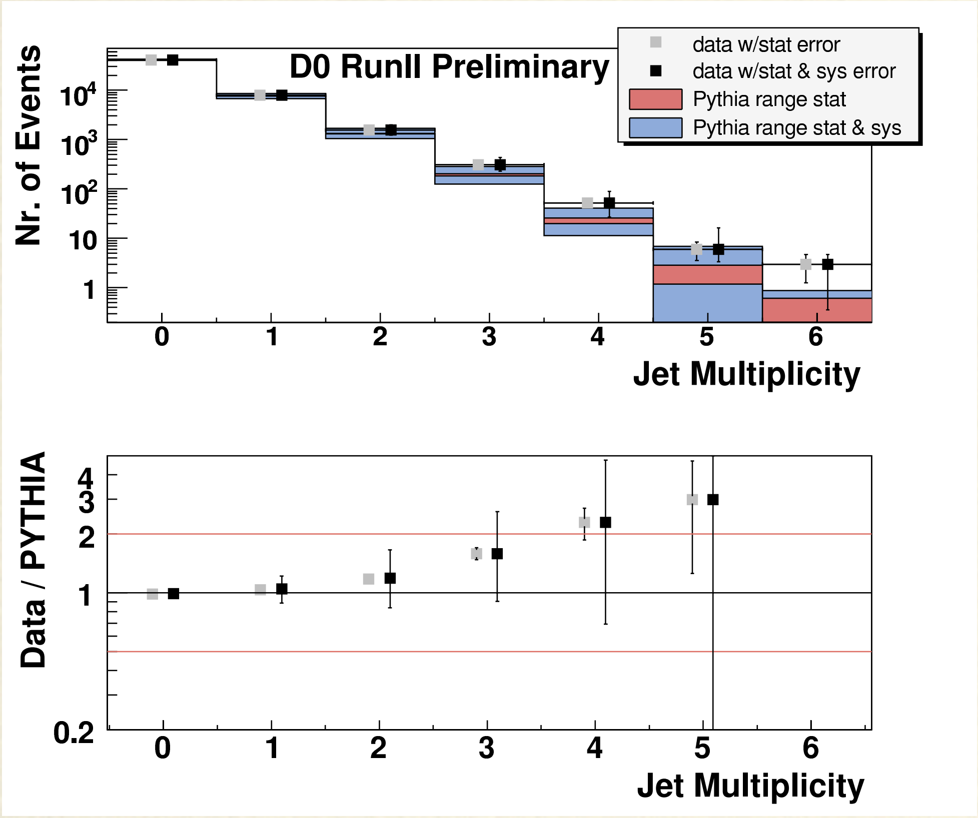
Alwall, de Visscher, Maltoni '08

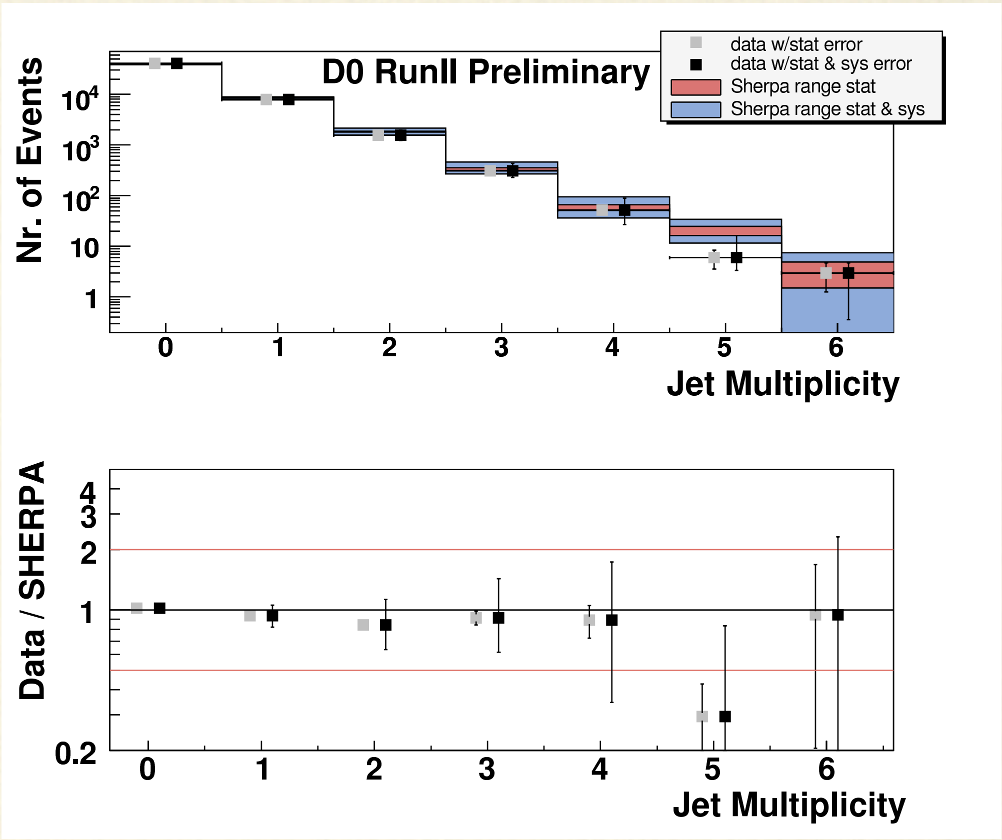


Matching reduces sensitivity of different PS parameters

Comparison with data

$\sim 1\ \mathrm{fb}^{-1}$





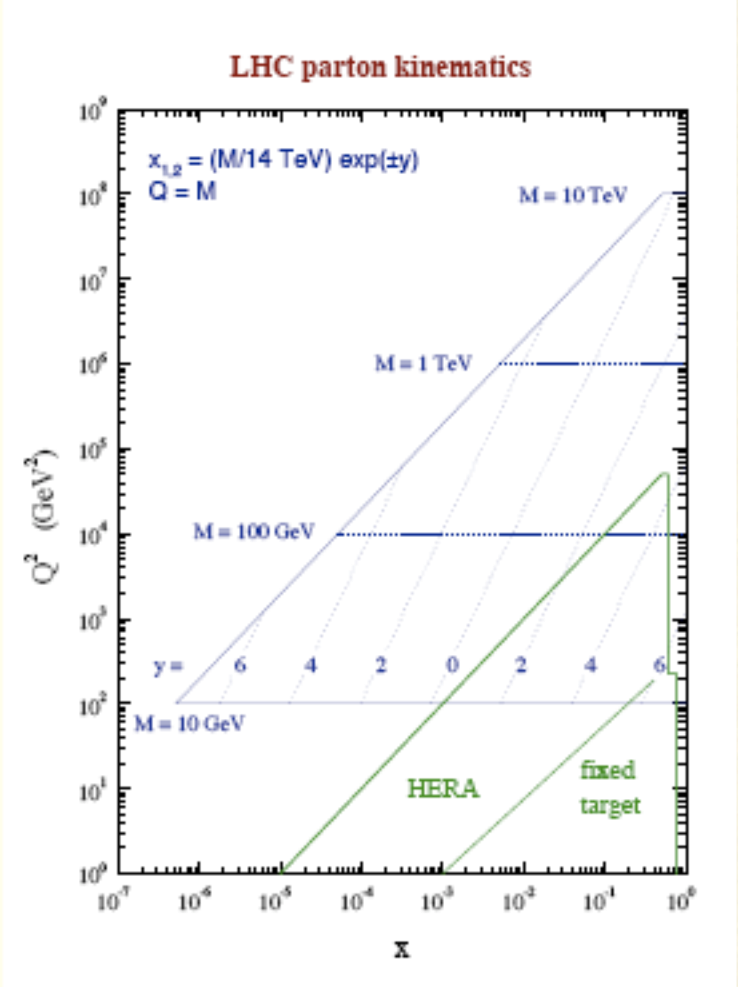
PS

ME+PS

Matching required for good description of Tevatron data

PDFs

R. Thorne



Enter every hadron collider prediction; better be understood

NNLO DGLAP kernels known

Moch, Vermaseren, Vogt '04

Fit data at $Q^2 = Q_0^2 \approx 2\ \mathrm{GeV}^2$

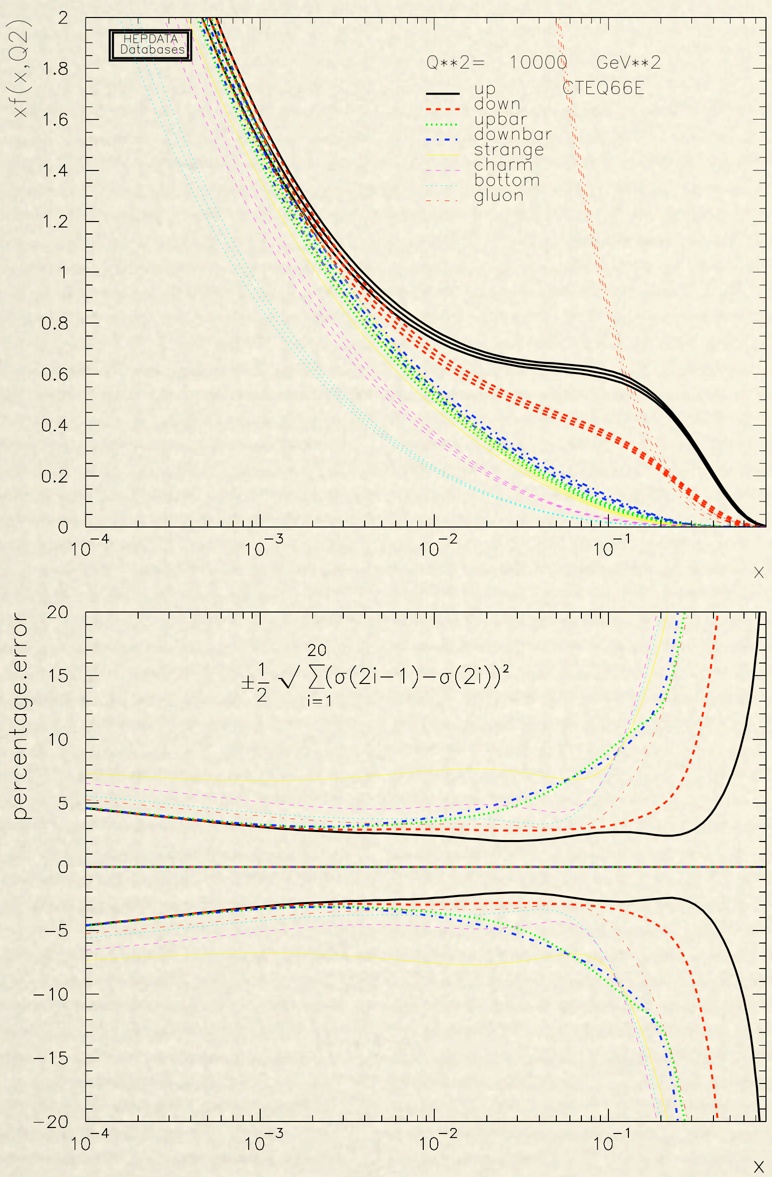
(Hera DIS, fixed-target DY, Tevatron jets, W charge asymmetry,...)

Fits by: Alekhin, CTEQ, MSTW, NNPDF

Some lattice efforts (LHPC, ...)

PDF errors

CTEQ 6.6 from HEPDATA



What do the errors mean?

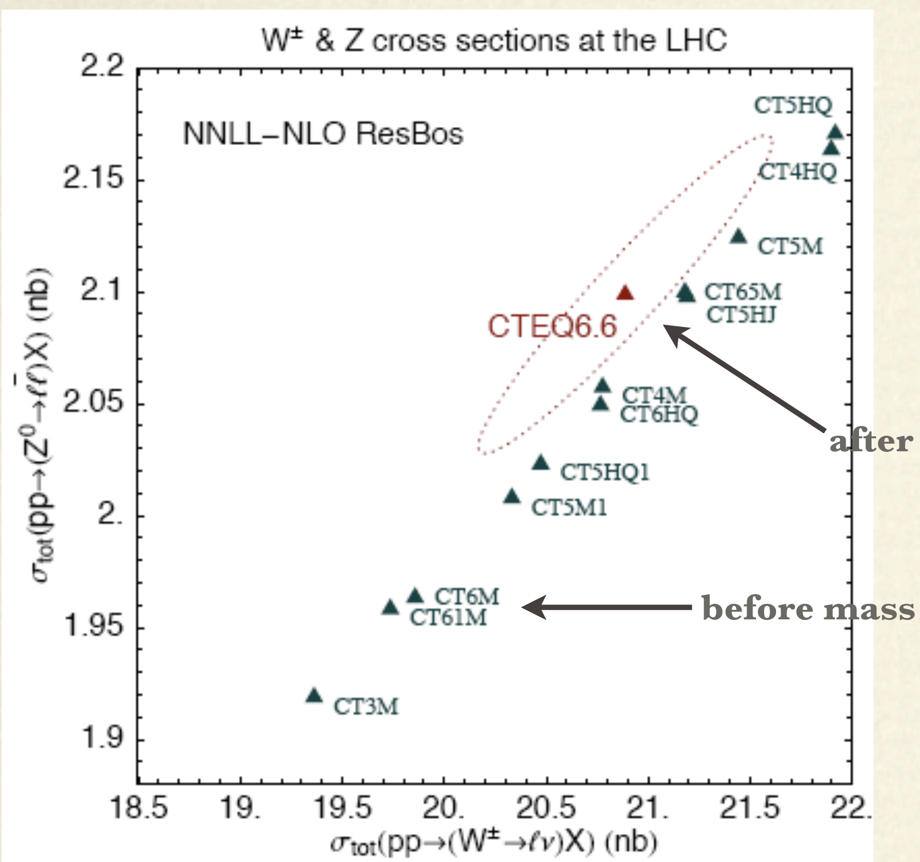
- There are many sources of uncertainty in the PDFs, some of which we've touched on
  - Data set choice
  - Kinematic cuts
  - Parametrization choices
  - Treatment of heavy quarks, target mass corrections, and higher twist terms
  - Order of perturbation theory
  - Errors on the data → ***Only* error included!**
- Techniques have been developed to handle the last one
- The others require judgement and experience, but *are not* included in what are generally referred to as PDF errors.

Excellent review by J. Owens at CTEQ 2007 summer school,
http://www.phys.psu.edu/~cteq/schools/summer07/

A good recent example...

Heavy quark mass effects

CTEQ, P. Nadolsky et al. '08



Better treatment of charm, bottom at threshold

F_2^c suppressed at $Q \sim m_c$

Increase $u, d, \bar{u}, \bar{d}$ to compensate

6% increase in predicted LHC W,Z; outside error estimate

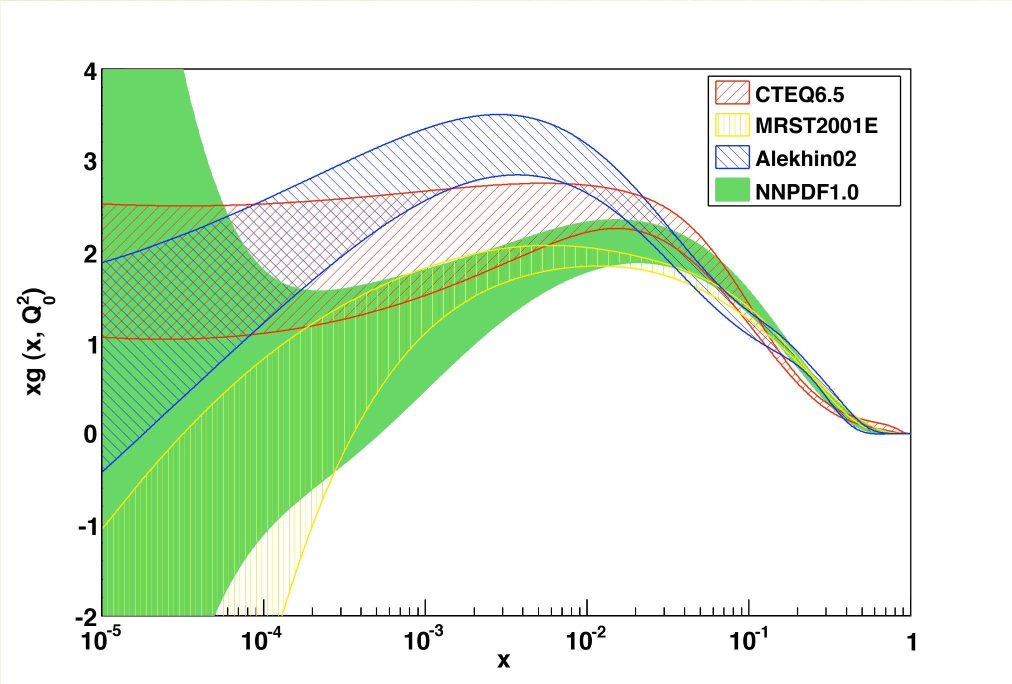
Given errors from only one source; not statistically rigorous; different theory, data sets, ... can have larger shifts!

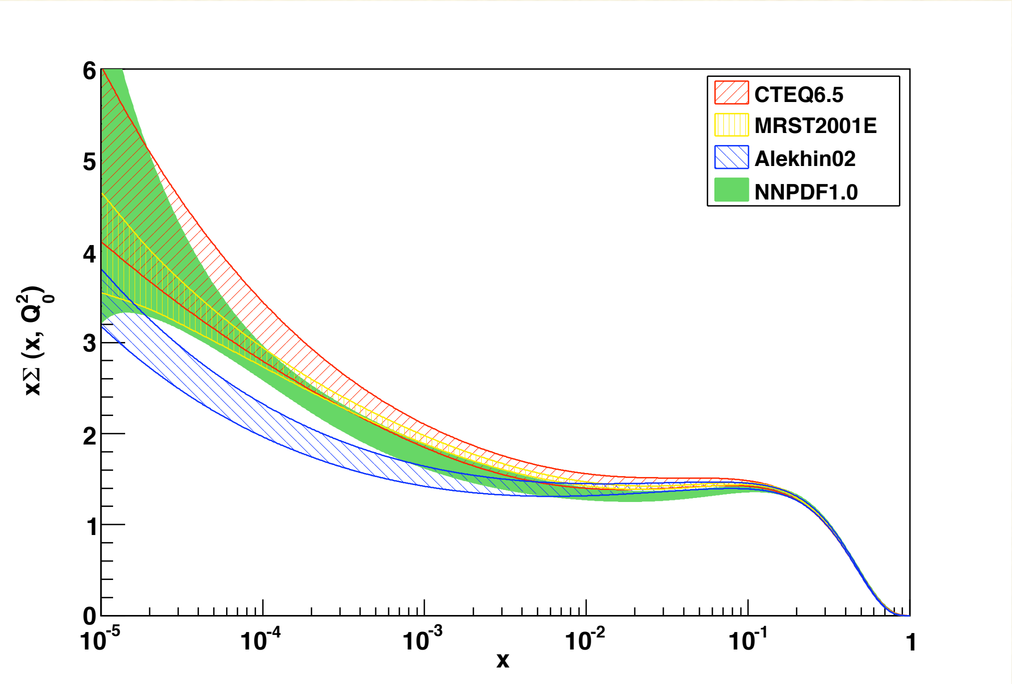
NNPDF and initial bias

Attempt to remove initial parameterization bias NNPDF:
Ball, Del Debbio, Forte, Guffanti, Latorre, Piccione, Rojo, Ubiala

Choose very redundant basis using neural nets

NNPDF '08



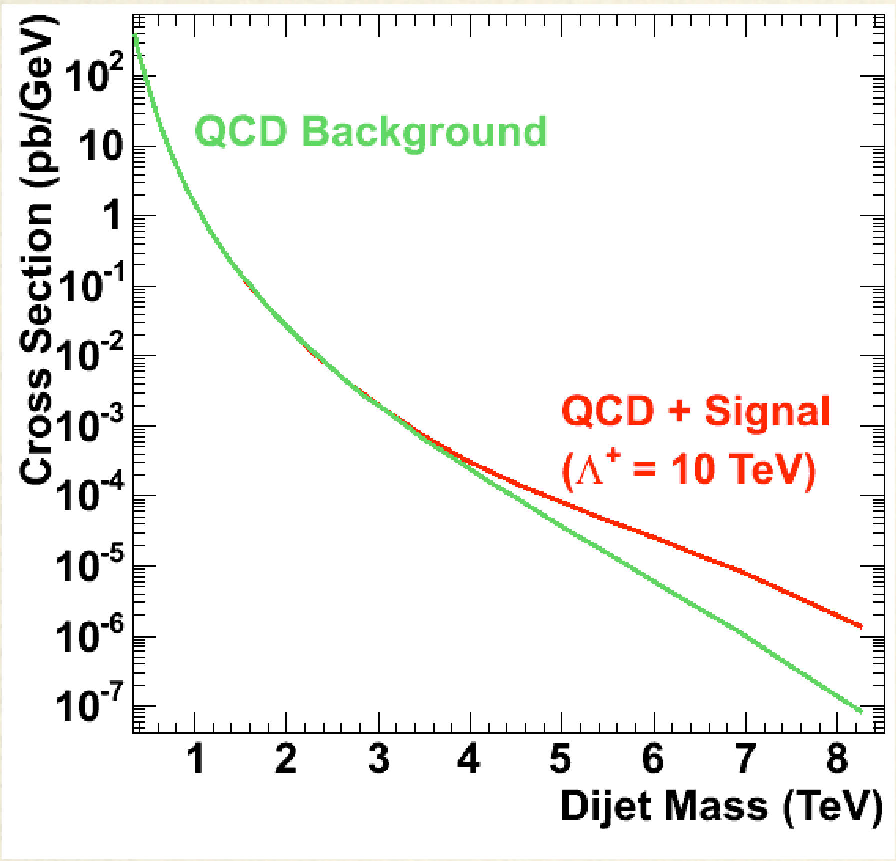


larger errors where data doesn't constrain (low-x gluon, singlet); does seem to have desired features

Not global fit yet, only DIS; stay tuned!

Conclusions

T. LeCompte, '07 CTEQ summer school



Lots of work needed to not confuse these two lines

Does new phase space at higher orders change the slope?

Are we using the right tool for this kinematic region?

Do we know x ~1 PDFs?

Lots of progress, much more to do!